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LASER ULTRASOUND FOR NONDESTRUCTIVE TESTING

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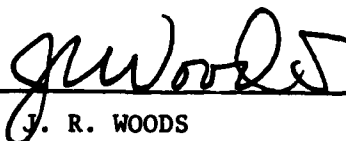Warminster, Pennsylvania 18974

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INTERIM REPORT

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Noncontact techniques for generating and detecting high frequency ultrasonic waves (> 1 MHz) are being explored using pulsed laser thermoelastic transduction and heterodyne interferometry respectively. In addition holographic projection techniques are being investigated for beam shaping and beam steering of the thermoelastic waves. Possible applications of this technology include performance of ultrasnic nondestructive testing in hostile or inaccessible environments.
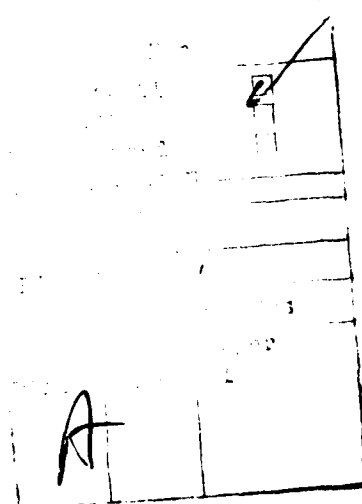
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INTRODUCTION

The technologies associated with thermoelastic wave generation and interferometric detection of vibration are well documented in the literature[1]; however, until very recently there has been insufficient quantitative data reported (particularly at MHz frequencies) to determine the practicality of implementing a nondestructive ultrasonic pulse echo system based on these concepts.

Certainly the remote non-contact capabilities of such a system would be advantageous in a number of NDT applications.

In addition the process of thermoelastic transduction has an advantage over piezoelectric transduction in that the energy delivered to a specimen can be accurately measured and it is not affected by intervening coupling media. On the other hand the efficiency of thermoelastic transduction is several orders of magnitude lower than piezoelectric transduction and the potential exists to produce material damage if the power delivered is too high.

Heterodyne interferometry has the capability for making localized non-contact absolute measurements of subangstrom displacements. Such localized measurements are not possible piezoelectrically; on the other hand, considerable increase in sensitivity is obtained with piezoelectric devices.

This report will summarize the NAVAIRDEVCEN Program in Laser Ultrasound, and a number of contractor efforts for establishing feasibility and implementing practical systems concepts. (See Figure 1).

Initial progress was in the area of laser generation of ultrasound. Studies in this area included determination of transduction efficiency for various materials and combinations of materials, characterization of beam profiles for thermoelastic waves, demonstration of flaw detection in aircraft materials, and demonstration of beam forming and beam steering. The latter work involved the implementation of a holographic concept developed at NAVAIRDEVCEN for increasing power and directivity of ultrasonic beams.

EXPERIMENTS AND RESULTS

Transduction

Initial experiments[2] were performed using a 40 - 150 watt pulsed nitrogen dye laser focused to between 5×10^{-3} cm and 0.1 cm diameter and having a 1.0×10^{-9} 5×10^{-9} sec. pulse duration. This laser was capable of producing light intensities between 1.3×10^3 and 1.9×10^6 watts/cm^2 at the surface of the specimens examined..

Using the above apparatus, thermoelastic waves were generated in a titanium plate (see Figure 2) and the resulting elastic wave was transmitted through an ambient water medium and received by a 10 MHz broadband transducer. The sample absorbed a 5 η sec. pulse with a power density of about 2.5×10^6 W/cm^2 producing an elastic wave with a signal amplitude of approximately 12 μ V. Correcting for reflection losses through the titanium, insertion loss of the transducer, bandwith of the receiver,

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[1] R. M. White J Appl Phys 34 p3559 (1963).

[2] NADC Report No. 78240-60

and assuming an effective 50 Ω transducer impedance, an acoustic power of 1.3×10^{-6} W was calculated for the resulting wave giving a transduction efficiency of 25×10^{-7}.

Von Gutfeld has compared this with the one dimensional analytical result given by White.[3]

$$|\eta| = \frac{5.7 \times 10^{-9} \, V\beta^2 \, Fo}{\rho C^2},\qquad (1)$$

where V is the acoustic phase velocity
   β is the linear thermal expansion coefficient
   ρ is the density
   C is the specific heat
   Fo is the thermal power density and
   η is the transduction efficiency

and obtains $(\eta) = \sim .5 \times 10^{-7}$

while the author has calculated a value of 1×10^{-7} using the same analysis. Although there is some discrepancy between these results, they are all of the same order of magnitude and indicate an efficiency significantly below that of piezoelectric devices. In the above example a peak power input of about 50 watts yielded an output signal of 12 V in a piezoelectric detector. The author has found that comparable power levels in piezoelectric devices yield signals on the order of tens of millivolts indicating a three to four order of magnitude increase in sensitivity by using piezoelectric transduction instead of thermoelastic transduction.

These results, however, should not be taken to mean that thermoelastic transduction is impractical since the region of excitation in the above experiment was very small ($\sim 2 \times 10^{-5}$ cm^2) and the power level, beam pattern, pulse duration and detection frequencies were not optimized. Clearly from expression 1 it is seen that transduction efficiency goes up linearly with power density which is limited by the material damage threshold.

In subsequent experiments, utilizing approximately 2.0 megawatts of laser power to illuminate 5.0 cm^2, signals comparable to those measured in piezoelectric studies were observed.

The author has done approximate calculations based on a theory by von Gutfeld and Budd[3] which indicate that, for some materials, thermoelastic surface displacement on the order of thousands of angstroms may be attainable at the high power densities described above, See Appendix A.

Such results will be discussed further in a later section in connection with holographic beam forming techniques.

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[3] R. J. von Gutfeld & H. F. Budd APL 34 #10 P617, 1979.

Thermal Effects

A major consideration limiting the use of laser generated ultrasound, is the material damage threshold associated with the production of thermoelastic waves. In addition to being undesirable from the view point of nondestructive testing, material damage phenomena, such as surface ablation and boiling or cavitation at a liquid-solid interface, distort the resulting elastic wave making it unsuitable for ultrasonic interrogation.

Von Gutfeld and Budd have performed calculations of the temperature per unit power density vs. time resulting from a pulse incident through water onto aluminum and steel surfaces.

The plot in Figure 3 indicates their experimentally verified result that no caviation effects exist below the range $\sim 10^6$ watts/cm^2, since temperature rise for this power level is below 75°C. In fact, experiments showed that most materials can be interrogated at power levels in the range 10^5 - 10^7 watts/cm^2 without specimen damage or signal distortion, and that one dimensional analytical heat flow model gave a reasonable estimate of the temperature rise in a specimen. The accuracy of these models is, however, dependent on surface absorptivity values which must be experimentally determined for most practical materials.

Beam Patterns and Beam Forming Techniques for Thermoelastic Waves

At least four techniques have been utilized for controlling the beam pattern of thermoelastic waves; (1) The use of a highly focussed laser beam[4] ($\sim 1 \mu$ diameter), which produces a spherically symmetric elastic wave, (2) The use of an expanded circular beam of diameter comparable to the ultrasonic wavelength,[5] which produces a collimated elastic wave of the type expected from a classical radiating piston, (3) The use of an expanded source[4] in conjunction with a hemispherical target, which focusses the thermoelastic wave producing a concentrated acoustic impulse at a given distance from the target. (This technique would be of primary use for creating waves in a liquid medium), and (4) The projection of a holographic image corresponding to the desired wavefront[6] producing any reasonable wave form and beam direction desired.

Of the four techniques tested above the use of projected holograms appears to be of most interest. In an experiment performed by Ih and Von Gutfeld 1/2" diameter holograms, produced on silver coated glass substrates were irradiated by a 1.6 megawatt pulsed YAG doubled green laser beam of approximately the same diameter as the hologram. The hologram (see Figure 4) itself was produced using a computer graphics system and photoetched onto the silver film. The hologram was designed to produce a focussed 2 MHz acoustic beam at a given distance from the hologram and at a 45° angle to the plane of the hologram (see Figure 5).

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[4] Von Gutfeld Private Communication.

[5] NADC Report No. 78240-60

Proposed by Scott and Ih and Confirmed
Experimentally by Ih and Von Gutfeld

Experimentally the device produced the desired focussing and steering characteristics at 2 MHz, ānd also exhibited a strong zero order peak (about a factor of 10 above the first order) normal to the hologram. For the case of a hologram designed to produce a focussed wave travelling perpendicular to the substrate, this zero order effect will be of little concern. A more important concern for normally as well obliquely propagating waves is the frequency dependence of the focussing and steering. In general, the narrower the frequency spectrum the sharper will be the focus and the narrower the deviation from the directed angle of the beam. Since the frequency spectrum of a single pulse thermoelastic wave is usually broad, techniques for producing rapid multiple pulses or for filtering pulsed signals may be required to produce sharp focussing and steering of beams.

Interferometric Detection of Ultrasound

As a non-contact device for measuring remote ultrasonic displacements, Bolt Beranek & Newman Inc (BB&N) have constructed a heterodyne optical interferometer. This is a device which measures very small ($\sim 1A^{o}$) high frequency displacements by measuring small changes in intensity resulting from fraction of a wavelength variations in distance. A conventional Michelson interferometer requires ultra stable vibration mounting to perform such measurements because of the effects of low frequency vibrations producing shifts in the background upon which the high frequency changes are superimposed. In the heterodyne form of the interferometer, an acoustic-optic modulator varies the patch difference in the two arms of the interferometer at a high frequency (~ 40 MHz). This effectively averages light intensity over a number of fringes thereby stabilizing the background upon which the intensity fluctuation is varied. Such an interferometer built by BB&N has been evaluated on both specularly reflecting and most finished metal surfaces. Operated at full bandwidth, this system had detection sensitivities of $5A^{o}$ and $20A^{o}$ respectively for these finishes. When narrow band detection was used with 0.1 second time averaging, this increases to .01 and .05A^{o}.

Although this sensitivity is considerably below that obtained with a piezoelectric device, the interferometer has the advantage that it can make measurements over a smaller region and thus is not subject to the phase cancellation effects found in piezoelectrics. A theoretical analysis indicated that the interferometer sensitivity was limited only by the laser intensity.

A protype model of this instrument is being constructed for evaluation by NAVAIRDEVCEN.

S U M M A R Y   A N D   C O N C L U S I O N S

Results in Appendix A indicate that, for at least some materials and surface finishes, it is possible to generate thermoelastic waves producing surface displacements on the order of hundreds of Angstroms. Assuming reasonable values for material losses and defect scattering factors, such waves should be detectable using the available interferometer technology which, under most conditions, should give sensitivity in the range of tens of Angstroms.

Focusing and steering of thermoelastic waves can be accomplished by distributing pulsed laser power in such a manner as to produce a holographic pattern corresponding to the wave front of a directional, converging ultrasonic wave. This technique appears to be preferable to point source excitation for other than near surface defects since it increases the maximum strain level of the ultrasonic wave produced and returns a stronger signal scattered from any flaw.

FUTURE PLANS AND RECOMMENDATIONS

Based on the above assessment, it is recommended that a facility be established to test an integrated system (see Figure 1) for the generation and detection of ultrasonic waves utilizing a high power pulsed laser ($\sim$ 10 MW peak power) and a stabilized heterodyne interferometer. Further work must be done in the study of beam steering and focusing particularly in the area of new ways to project holograms, (e.g. multiple pulsed systems, acousto-optic modulators, double beam interfering systems).

The interferometric detection system must also receive additional attention. This device has the potential of serving as an absolute system for calibrating and characterizing the beam patterns of all types of ultrasonic devices. Another requirement in this area is the design of a scanner which would allow the interferometer to scan over a finite area; such a scanner could conceivably be used to move both the pulse beam and the interferometer beam. Such a prototype laser ultrasonic system could probably be constructed within the next fiscal year and be tested on a variety of aircraft materials and components.

FOCAL POINT OF THERMOELASTIC WAVE

DEFECT

IMAGE OF CONVERGING WAVE FRONT

RETURNING WAVE FRONTS

DICHROIC MIRROR

SPECIMEN

HETRODYNE INTERFEROMETER (RED LASER)

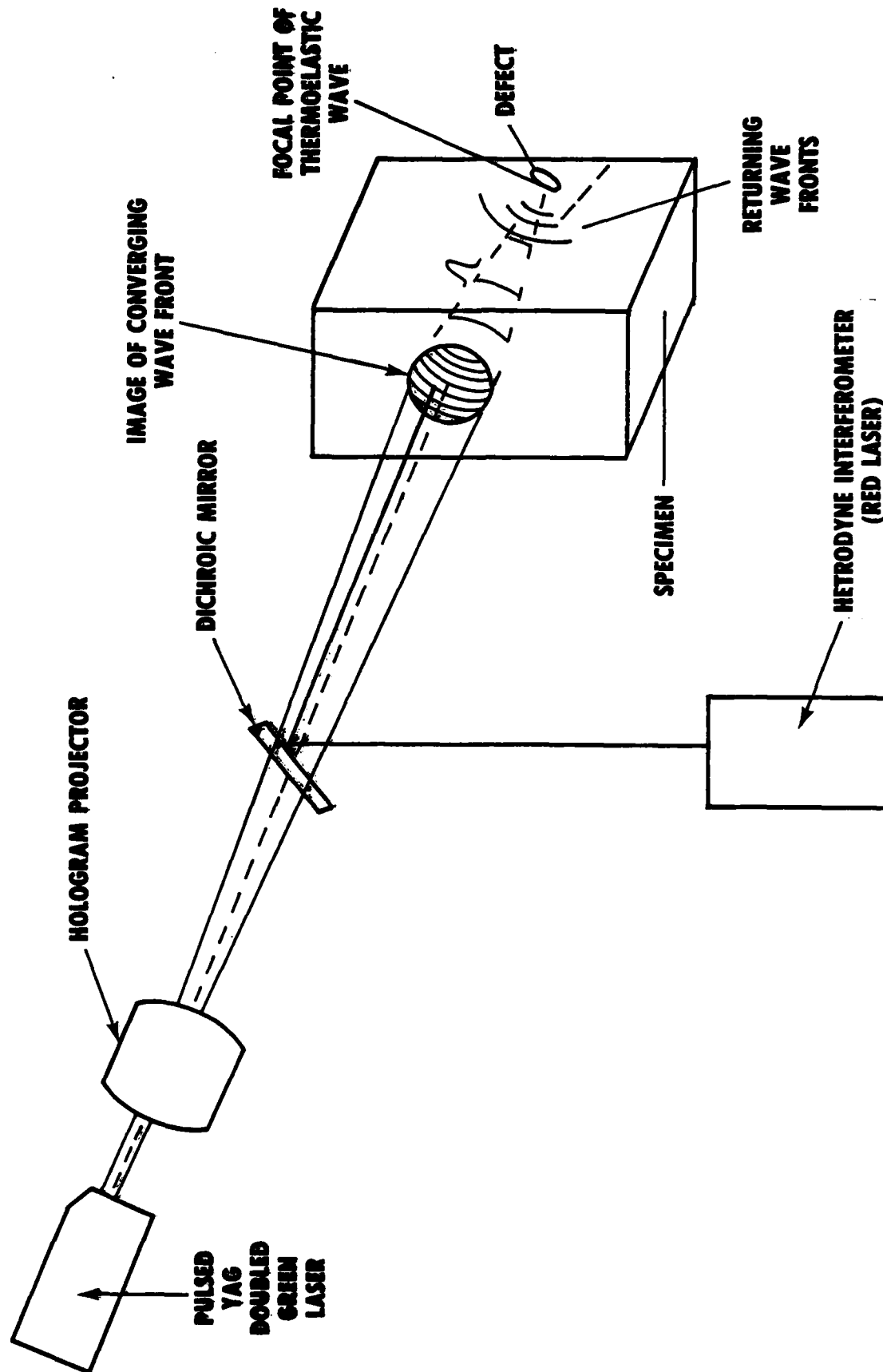HOLOGRAM PROJECTOR

PULSED YAG DOUBLED GREEN LASER

Figure 1. Schematic of a Possible System for Pulsed Laser Generation and Interferometric Detection of Ultrasound
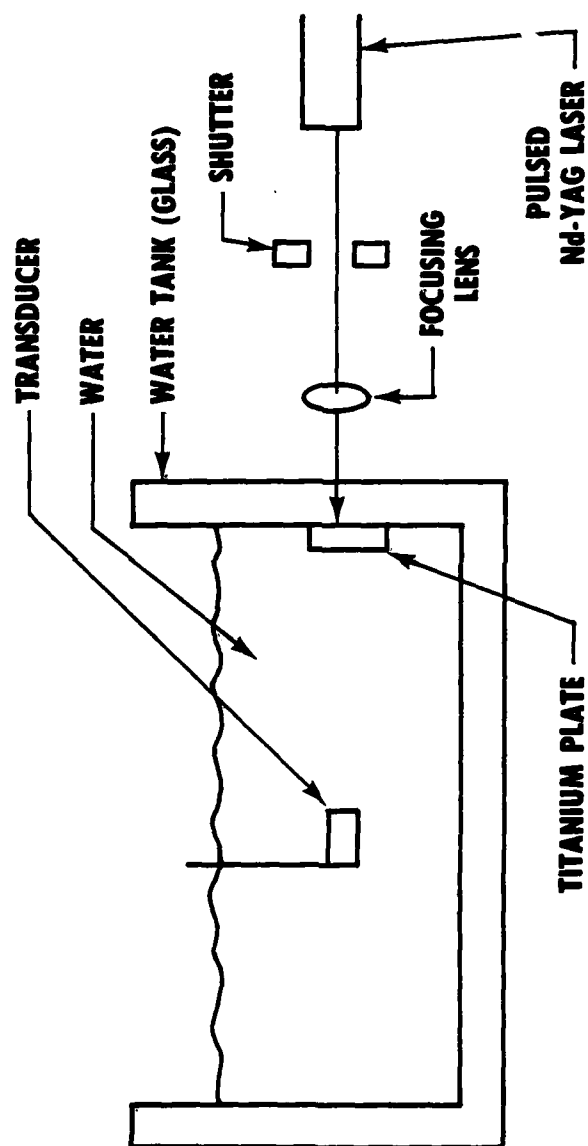
Figure 2. Apparatus for Exciting and Detecting Thermoelastic
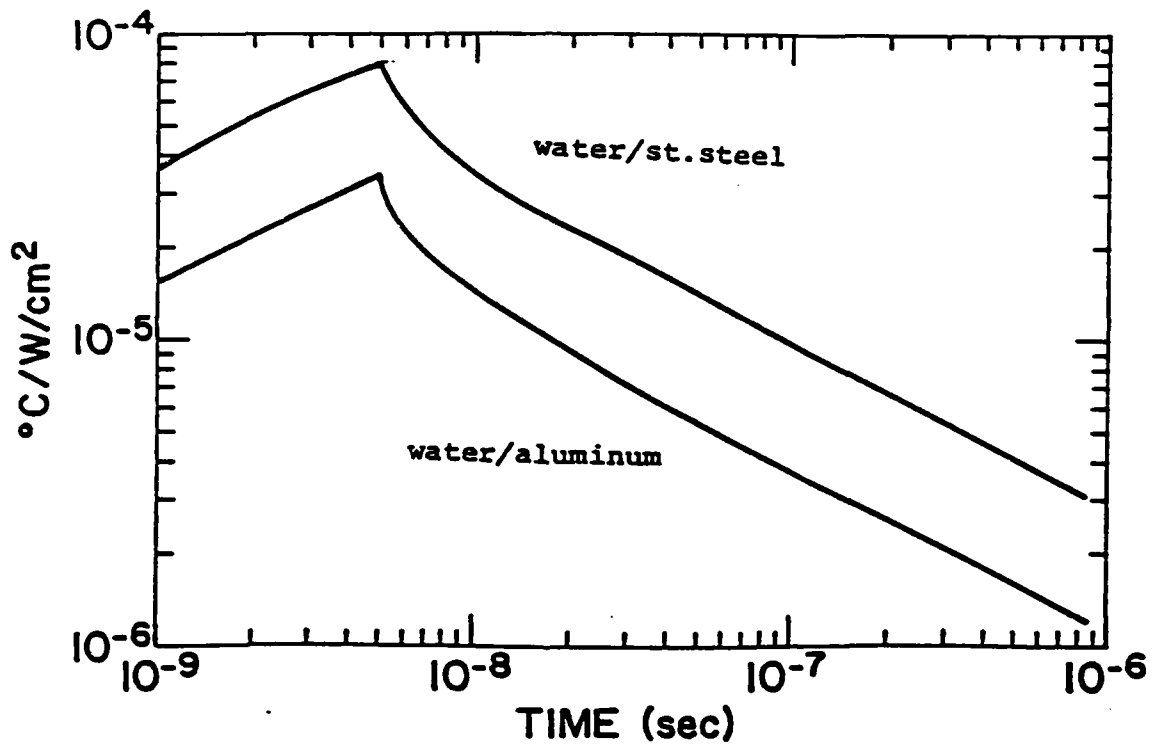Waves in Titanium

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FIGURE 3. TEMPERATURE RISE PER UNIT POWER DENSITY FOR 5 n sec LASER PULSE INCIDENT UPON WATER/STEEL AND WATER ALUMINUM INTERFACES
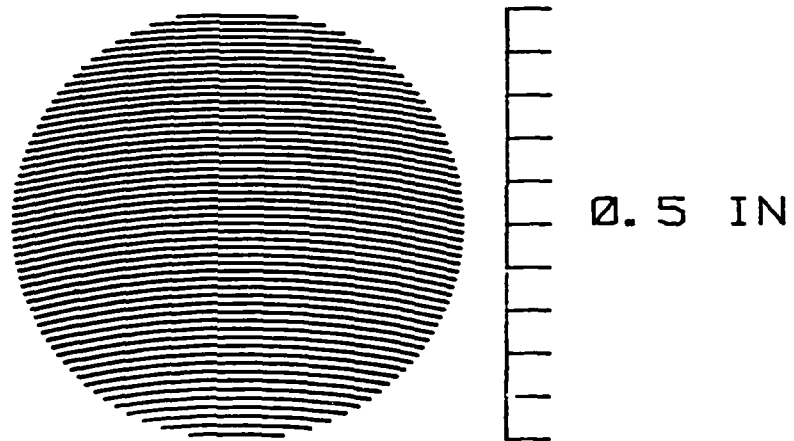
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Figure 4.   A Hologram Produced Using a Computer Graphics System
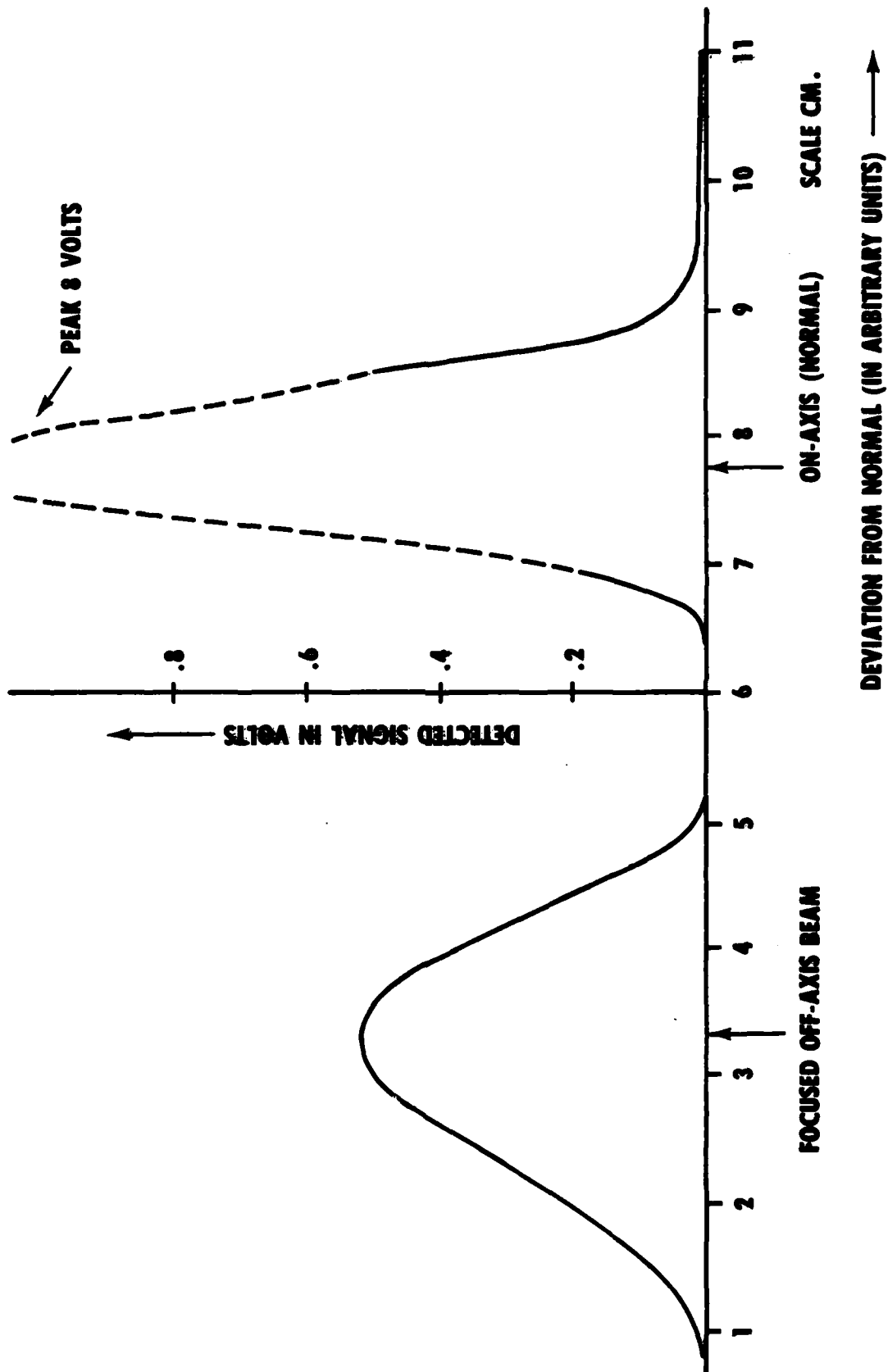
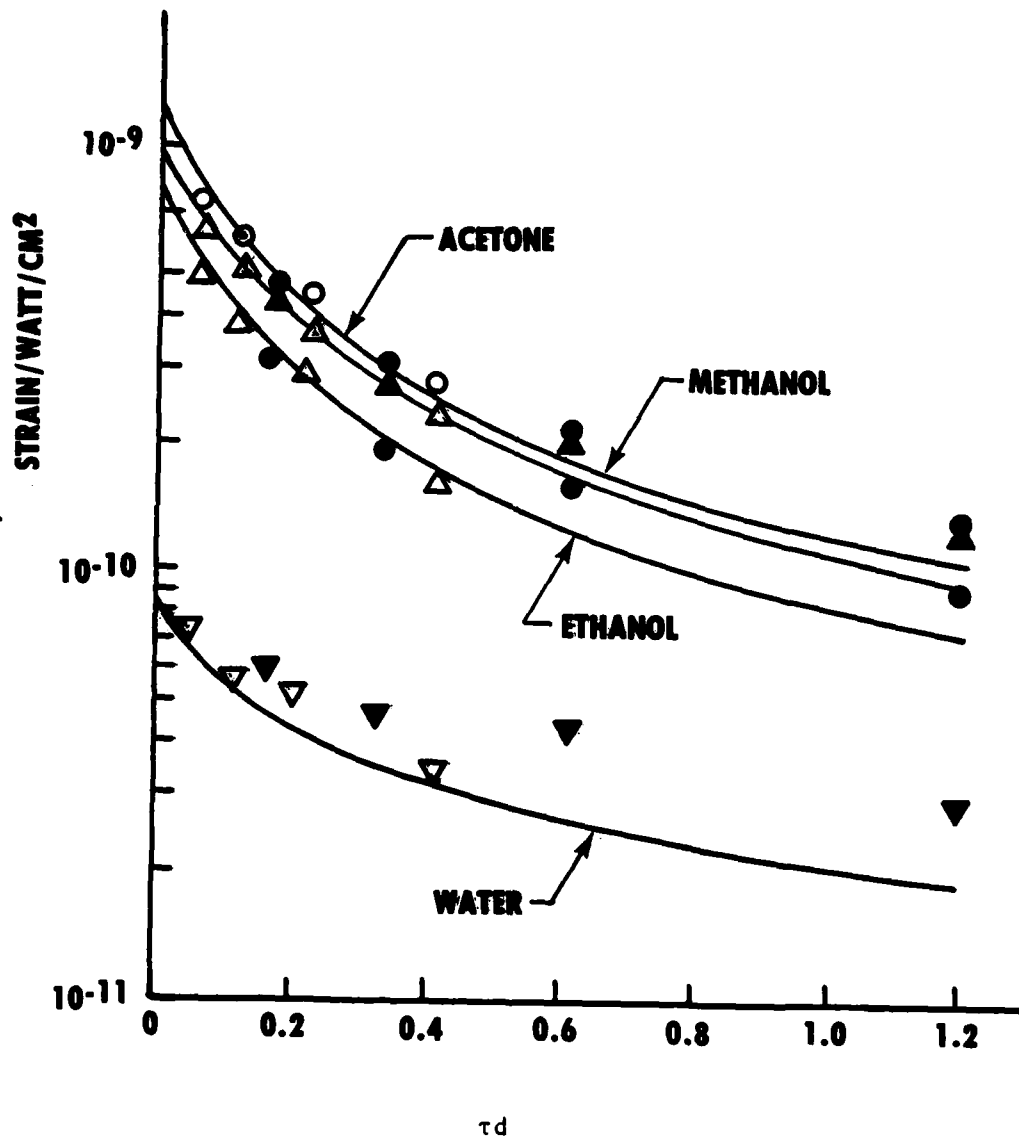Figure 5. Beam Profile for Thermoelastic Wave Produced Using Hologram of Figure 4

Figure 5.   Maximum Relative Strains for Various Thermal
Skin Depths as Calculated by von Gutfeld and Budd

APPENDIX A

DISPLACEMENTS RESULTING FROM LASER PULSES

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A P P E N D I X   A

Figure 6 above indicates that for reasonable laser power densities on the order of 10^5 watts/cm^2, maximum strain on the order of 10^{-4} to 2×10^{-6} would be expected. If a longitudinal elastic wave having peak frequencies in the range of 10 MHz were generated with short laser pulses, the resulting waveform might reasonably be approximated by 1/2 cycle of a 10 MHz sine wave.

The total displacement associated with such a wave would be given by

$$\mu_{Total} = \epsilon \, max \int_{0}^{T/4} \sin \frac{2\pi x}{T} \, dx = \frac{T \, \epsilon \, max}{\pi}$$

where ϵ max is the maximum strain T is the wavelength of the sine wave (on the order of $\frac{1}{2}$ mm) and μ_{total} is the total displacment.

This yields displacements in the range of 5 to 500 Angstroms.

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